How One Equation

The world's most famous equation, E = mc^2, revolutionized physics, redefined strategic arms, and promises to transform our economy and environment with plentiful, clean energy.

In many respects, Lawrence Livermore's national security and energy missions are part of—and a tribute to—Albert Einstein's legacy. A number of Livermore research projects are linked to a three-page paper written by Einstein in September 1905. This short paper, which contained no footnotes or references, turned physics upside down by linking mass and energy in a way never before postulated.

Published in the German journal *Annalen der Physik*, the paper was entitled "Does the Inertia of a Body Depend on Its Energy Content?" It was a supplement to Einstein's work on special relativity that appeared in the same physics journal earlier that year. The text begins: "The results of an electrodynamic investigation recently published by me in this journal lead to a very interesting conclusion, which will be derived here."

The paper applied the special theory of relativity to light being emitted from a stationary object. Einstein concluded that if a body emits an amount of energy, E, in the form of radiation, then its mass, m, must be reduced by the amount E/c^2, where c is the speed of light. This reasoning led to the equation $E = mc^2$, probably the most famous equation in the world. $E = mc^2$

Changed the World

does not appear explicitly in the 1905 paper; however, it does appear in Einstein's later work in 1906 and 1907.

Because the speed of light is a very large number—299,792,458 meters per second—and is multiplied by itself, a small amount of matter is equivalent to an enormous amount of energy. For example, a kilogram of mass converts to 21 million tons of TNT energy.

Einstein did not expect his result to be easily confirmed because it would have been too difficult to measure the small amounts of mass converted in the radiation emissions that were experimentally accessible at the time. He concluded his paper by conjecturing that radioactive materials, such as radium salts, might provide a means to test the theory.

Full confirmation of the equation did not occur until the 1930s, following elucidation of the structure of the nucleus as an assemblage of neutrons and protons. In 1932, James Chadwick discovered the neutron. That same year, John Cockcroft and E. T. S. Walton bombarded a lithium nucleus with a proton and produced a nuclear reaction. The experiment demonstrated the accuracy of Einstein's equation by showing that a small amount of mass could be converted into energy. One year later, Irène and Frédéric Joliot-Curie demonstrated the reverse process, when they took a photograph showing the conversion of energy into subatomic particles.

Over time, scientists grew to realize that huge amounts of energy could be liberated in nuclear reactions, such as those that occur in the Sun and stars. (See the box on p. 17.) For example, the Sun fuses hydrogen nuclei (protons) into helium nuclei (containing two protons and two neutrons each), a process called fusion that goes on for billions of years. The masses of the protons at the start of a fusion event are slightly heavier than the mass of the helium nucleus at the end of the process: the missing mass is converted to energy. For stars more massive than the Sun, the carbon–nitrogen–oxygen cycle is the primary vehicle for fusing hydrogen nuclei into helium nuclei.

Today, in a nuclear reactor, a heavy element, such as uranium, is split into two lighter elements during a process called fission. Once again, the combined mass of the products is lighter than the original nucleus. The difference in mass is converted to energy, which is used for boiling water to drive turbines.

Probing Subatomic Particles

$E = mc^2$—together with the development of quantum mechanics and advances in nuclear physics—spawned new kinds of experiments in which physicists bombard targets with high-energy subatomic particles. Sometimes the particle collisions lead to new particles. In this respect, turning energy into matter is a well-tested method of uncovering the substructure of the universe.

In one such project, Livermore physicists Peter Barnes, Doug Wright, and Ed Hartouni are participants in an international experiment centered at the Fermi National Accelerator Laboratory (Fermilab) in Illinois. The experiment focuses on measuring how one type of neutrino transforms into another type, a process called oscillation. (See *S&TR,* April 2003, pp. 13–19.) The results promise to help scientists better understand particle physics as well as the role of neutrinos in the universe. "Without $E = mc^2$," says Barnes, "scientists might not have postulated the neutrino. Particle physics would be completely different; the field would be mainly a mystery."

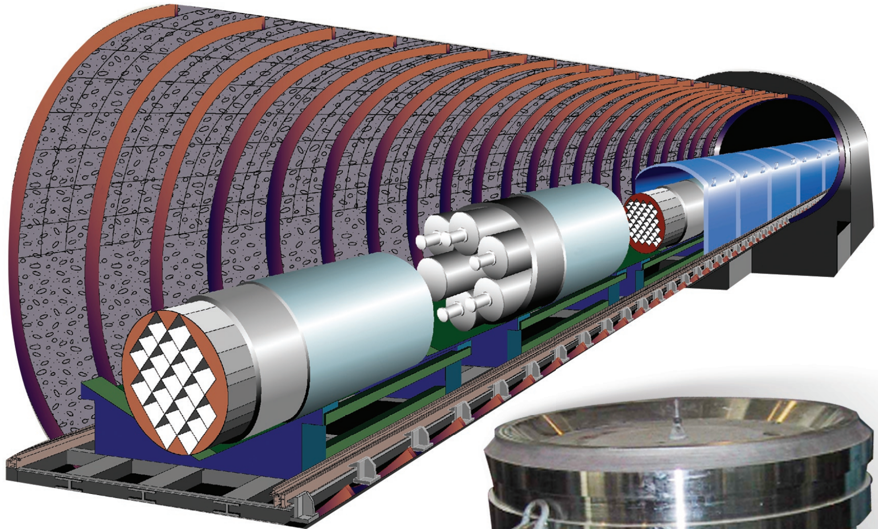
Neutrinos, the most mysterious of subatomic particles, are difficult to detect because they rarely interact with other forms of matter. Although they can easily pass through a planet or solid walls, they seldom leave a trace of their existence. Three types of neutrinos exist—the electron neutrino, muon neutrino, and tau neutrino, which are related, respectively, to the common electron and the less common muon and tau particles. Evidence of neutrino oscillations proves that neutrinos are not massless but instead have a mass less than one-hundred-thousandth that of an electron.

The Fermilab experiment, called the Main Injector Neutrino Oscillation Search (MINOS), uses a neutrino beamline, completed in early 2005, that has an energy spectrum of 0.5 to 8 gigaelectronvolts. One goal of the MINOS experiment is to discover the rate at which neutrinos "change flavors," or oscillate from one type to another.

The MINOS researchers use two giant detectors—one at Fermilab and a 6,000-ton detector lying in a historic iron mine at Soudan, Minnesota. A narrow beam of neutrinos is generated and characterized by the near detector at Fermilab. The beam is aimed at the far detector in Minnesota. The neutrino beam energy is chosen so that the distance between the two detectors corresponds to an expected maximum in the probability that a neutrino produced at Fermilab will oscillate to another flavor. Physicists compare the muon neutrino beam flux and spectrum measured by the near detector with that from the far detector in Minnesota to understand the properties of neutrino oscillations. In this way, they can determine the relative mass differences between the neutrino types.

Livermore physicists are also part of a project funded by the Laboratory Directed Research and Development (LDRD) Program to analyze data needed

The Main Injector Particle Production (MIPP) experiment at Fermi National Accelerator Laboratory (Fermilab) will measure subatomic particle production from beams of protons, pions, and kaons. Livermore physicist Peter Barnes (right) works on one of the experiment's detectors, called the Time Projection Chamber. Also shown is Fermilab technician Walt Jaskierny.



Livermore researchers are developing prototype canisters that would house nuclear waste as part of the Department of Energy's program to design, license, and build an underground waste repository in Yucca Mountain, Nevada.

to accurately model the MINOS neutrino beam. The Fermilab Main Injector Particle Production (MIPP) experiment measures particle production from proton, pion, and kaon beams, ranging from 5 to 120 gigaelectronvolts, directed on targets, including liquid hydrogen, beryllium, copper, carbon, bismuth, and depleted uranium. Pions and kaons are mesons, which help to bind the nucleus.

Barnes explains that the kinetic energy of the incoming beam is converted into new particles, including pions, the precursors to the muon neutrinos in the MINOS beam. Scientists are measuring the species that are produced, their energies, and the angle at which they leave the target.

MIPP results will aid Livermore's stockpile stewardship efforts. Livermore has been exploring the use of high-energy protons to create radiographs similar to x-ray images. (See *S&TR,* November 2000, pp. 12–18.) Proton radiographs could be used in stockpile stewardship to image deep inside explosive experiments and obtain information about materials too dense for x rays to penetrate. However, proton radiographs tend to be blurry, in part because the proton beam that reaches the detector also contains subatomic particles produced as the beam passes through the object being imaged. Stockpile stewards need to know the exact identity of these secondary particles and how they affect the final image in order to make quantitative measurements.

New Uses for Warhead Material

$E = mc^2$ and subsequent advances in quantum and nuclear physics ushered in a new age of energy production without carbon emissions or depletion of nonrenewable hydrocarbon fuels. Nuclear energy supplies 20 percent of the electricity in the U.S. and 16 percent of that used throughout the world. Livermore researchers have long worked on different aspects of nuclear energy. For example, as part of the Department of Energy's (DOE's) program to design, license, and build an underground nuclear waste repository in Yucca Mountain, Nevada, the Laboratory is designing a waste package and barrier system. Researchers have also developed computer codes that predict the performance of the system for thousands of years.

Livermore nuclear experts are also helping to oversee an unusual source of uranium fuel for U.S. power plants. The collapse of the Soviet Union created a grave threat of proliferation, with hundreds of weapons and thousands of kilograms of weapons-usable materials potentially at risk to theft and misuse.

Signed in 1993, the Highly Enriched Uranium (HEU) Purchase Agreement between the U.S. and the Russian Federation commits the U.S. to purchasing 500 metric tons of HEU (90 percent ^{235}U) extracted from dismantled Russian nuclear weapons over a period of about 20 years. The U.S. receives low-enriched uranium (LEU), which has been blended down from HEU so that it contains less than 5 percent ^{235}U. The LEU is used as fuel in U.S. commercial nuclear power reactors.

Currently, Russian plants are processing about 30 metric tons of HEU per year into about 875 metric tons of LEU. This amount meets half the annual fuel requirement for U.S. nuclear power plants and provides the fuel to generate 10 percent of the electricity used in the U.S.

The Highly Enriched Uranium Transparency Program provides confidence that Russian LEU sold to the U.S. under the 1993 agreement is derived from dismantled Russian nuclear weapons. The program monitors the Russian process of converting weapons-usable HEU into LEU. A Transparency Monitoring Office was established in 1996 by DOE and is staffed in part by Livermore workers.

Livermore physics and nuclear chemistry experts, headed by engineer

Al DiSabatino, use portable, nondestructive assay equipment to ensure that the HEU, checked in closed containers, is 90 percent ^{235}U. In addition, the U.S.-supplied Blend Down Monitoring System provides a continuous, unattended, and independent monitoring of the blending process at Russian facilities. Experts from Livermore and other DOE laboratories and contractors make transparency-monitoring visits to each of the four Russian uranium-processing facilities. The Russian Federation also monitors U.S. facility operations to ensure the peaceful use of LEU delivered to the U.S.

DiSabatino notes that the HEU Purchase Agreement will reach a historic milestone this year—the conversion and permanent elimination of 250 metric tons of HEU from Russian stockpiles, the equivalent of 10,000 nuclear devices and the halfway point toward the goal of eliminating 500 metric tons of HEU.

Advancing Nuclear Power

Livermore researchers are also working on advanced nuclear fuels and fuel-cycle technologies that are cleaner, more efficient, and more resistant to proliferation. For example, nuclear engineer Jor-Shan Choi, chemist Bart Ebbinghaus, and mechanical engineer Tom Meier, funded by LDRD, are developing fuel for the small, sealed, transportable, autonomous reactor (SSTAR).

SSTAR, a DOE collaborative project, is a liquid-metal cooled, fast reactor that can supply 10 to 100 megawatts of electrical power. The reactor will measure about 15 meters tall by 3 meters wide. Its weight will not exceed 500 tons, so it can be transported by ship or heavy transport truck. (See *S&TR,* July/August 2004, pp. 20–22.)

By using lead or lead–bismuth as a cooling material instead of water, high-pressure vessels and piping normally needed to contain reactor coolant will not be necessary. Nuclear fuel will be contained within the sealed, tamper-resistant reactor vessel, which will be shipped to the user country and returned to the supplier country without the need for it to be opened during its anticipated operating lifetime of about 30 years. Because the reactor uses no refueling or onsite storage of spent fuel, the reactor will not raise concerns about diversion of nuclear materials and nuclear proliferation.

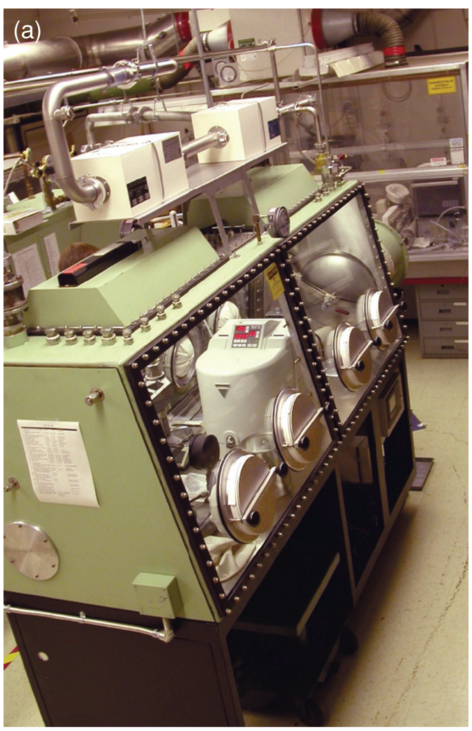
"With a typical nuclear power plant, some of the spent fuel must be removed every 12 to 18 months," says Choi. "With SSTAR, onsite refueling and long-term storage of radioactive wastes is not necessary."

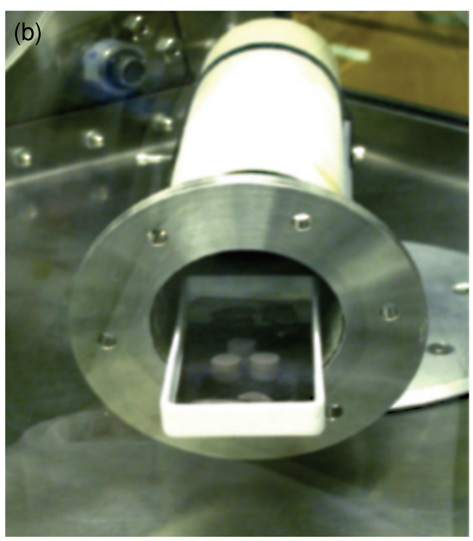
The requirements for a sealed, long-life reactor impose significant challenges to developing the nuclear fuel and its cladding. Factors that affect the selection of the reactor fuel for SSTAR include coolant compatibility, economics, long life, proliferation resistance, and safety. The Livermore team chose an advanced mononitride-based fuel because of its suitability for a liquid-cooled fast reactor and its potential to meet other selection factors. Choi notes that the National Aeronautics and Space Administration and DOE have identified mononitride-based uranium fuel as one of the preferred fuels for nuclear reactors used in space exploration.

The selected fuel's thermal conductivity is 10 times higher than traditional uranium oxide, and its melting temperature is much higher than that of metal fuel. To ensure that the uranium in the fuel is not attractive for use in clandestine nuclear weapons, the ^{235}U enrichment is limited to 20 percent and contains inert materials not readily separated from the fuel.

The research team is using recently constructed laboratories at Livermore to develop advanced nitride-based reactor fuel pellets. Researchers are evaluating the pellet's characteristics and verifying their quality. In optimizing the formulation, the team is using additives such as zirconium and hafnium nitrides for improved stability and burn-up characteristics. Samples of the manufactured fuel pellets will undergo irradiation tests.

An important element of the project is applying Livermore's modeling capability





Livermore researchers are developing fuels for the small, sealed, transportable, autonomous reactor (SSTAR). (a) A glove box was used to manufacture mono-uranium-nitride powder, which was then (b) hydraulically pressed and heated into small pellets.

Tapping the Potential of the Nucleus

The neutrons and protons are kept stable in every atom's nucleus by attractive nuclear forces. The relative stabilities of the nuclei of different elements are determined by their binding energies, that is, how much energy is required to remove a proton or neutron from the nucleus. If the binding energy of each nucleus is plotted as a function of the number of protons and neutrons it contains, a curve of binding energy is obtained.

As seen in the figure below, nuclei with a small number of neutrons and protons have a low binding energy. Such nuclei are easier to break apart and are not as stable as nuclei with larger numbers of protons and neutrons. As the number of neutrons and protons increases, the binding energy reaches a peak and then drops off again. Nuclei at the peak are the most tightly bound and correspond to elements near iron in the periodic table. As neutrons and protons continue to be added, the nucleus becomes less tightly bound.

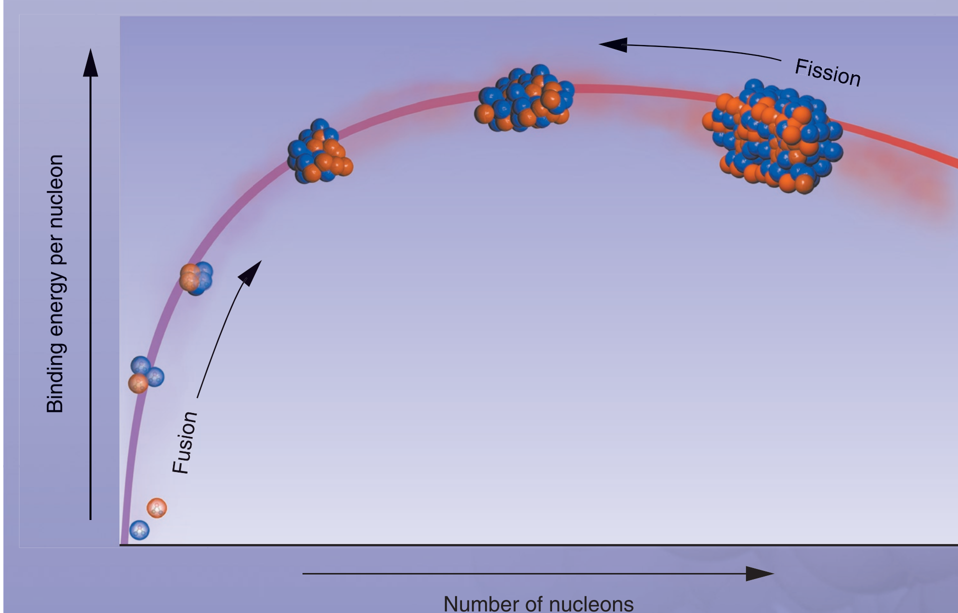
If uranium and plutonium nuclei, at the far right end of the plot, break into smaller nuclei, the pieces are harder to break apart. Thus, if a way can be found to break a uranium or plutonium nucleus, energy will be released. This process, known as fission, is typically started by trickling neutrons into such nuclei. The neutrons give these nuclei just enough energy to undergo fission. When such nuclei split, extra neutrons are given off. Under the right conditions, a self-sustaining set of reactions can occur in which more and more fissions occur. This process can either lead to a runaway reaction, as in a fission bomb, or can be kept at a steady state, as in a nuclear reactor.

If very light nuclei such as hydrogen or deuterium are forced together, in a process called fusion, the resulting nucleus is in a lower energy state, and the extra energy is given off as radiation or energetic neutrons. This fusion process is more difficult to achieve than fission because the electrical repulsion of the nuclei must be overcome to get the nuclei to fuse. In the center of the Sun and other stars, nuclei have the very high temperatures and densities required for thermonuclear fusion.

The high temperatures and densities required for fusion have been achieved on Earth for only very short periods of time in thermonuclear bombs and a few research machines such as fusion tokomaks and the Laboratory's Nova laser, which operated from 1985 to 1995.

Controlled fusion for energy production is being attempted in two different ways: magnetic fusion and inertial confinement fusion. In magnetic fusion, intense magnetic fields confine low-density plasma at temperatures and densities needed for fusion. In inertial confinement fusion, lasers or accelerators compress extremely small pellets to the very high densities and temperatures needed for fusion.

It is interesting to compare the temperatures, densities, and confinement times of these approaches. Confinement time is the amount of time it takes for the energy in the plasma to be released. Magnetic confinement requires densities of only 10^{-9} grams per cubic centimeter, temperatures of roughly 100 million kelvins, and a confinement time of several seconds. Inertial confinement requires densities of 1,000 grams per cubic centimeter, temperatures of about 100 million kelvins, and confinement times of 10^{-11} seconds. The center of the Sun is calculated to reach densities of greater than 100 grams per cubic centimeter and temperatures of 16 million kelvins. Because of gravitational forces, the Sun's confinement time is as long as the age of the Sun.



Nuclei with a small number of neutrons and protons have a low binding energy. As the number of neutrons and protons increases, the binding energy reaches a peak and then drops off. Uranium and plutonium nuclei are at the far right end of the plot. If they break into smaller nuclei (fission), the pieces become more bound. For very light nuclei such as hydrogen or helium, more nuclear binding energy can be obtained if the nuclei are forced together (fusion).

to study nuclear fuel performance. Computer codes will determine how many years the advanced fuels will likely last.

Choi says successful development of the fuel should make nuclear power more acceptable for worldwide use, including in developing nations.

Two Roads to Nuclear Fusion

Like nuclear fission, controlled nuclear fusion could generate electricity without producing atmospheric pollution. Thermonuclear fusion of hydrogen is the energy source for the Sun and the stars. For equal amounts of fuel, the energy from fusion is about 1 million times greater than that released from burning fossil fuels. For such fusion reactions to proceed at high enough rates to be practical, the fusion fuels (heavy hydrogen) must be heated to temperatures of about 100 million degrees Celsius. Two ways are being pursued to contain fusion fuel at the required temperature and density: magnetic confinement and inertial confinement.

The earliest controlled fusion effort at Livermore focused on magnetic confinement, in which deuterium fuel is trapped in a magnetic field for extended periods of time. In this concept, the fuel is at typically 100,000 to 1 million times lower density than air. These low densities are needed for sustained confinement at pressures corresponding to the high temperatures needed for fusion.

Research during the early years of this effort, called Project Sherwood, was classified because, if successful, it could have provided a prodigious source of 14-megaelectronvolt neutrons for breeding plutonium from uranium.

Magnetic confinement fusion was of interest to scientists on both sides of the Cold War. In the late 1950s, the Livermore program was declassified and has now evolved to be a part of the Laboratory's Fusion Energy Program. Today, Livermore researchers collaborate with General Atomics in San Diego, California, on tokamak fusion reactors. An alternative to the tokamak concept is Livermore's Sustained Spheromak Physics Experiment, built in 1997. (See the article on p. 4.)

Livermore researchers have developed advanced computational models to study magnetic fusion reactions. Results of these simulations will aid the International Thermonuclear Experimental Reactor (ITER), for which Livermore led the conceptual design activity. The 10-meter-diameter ITER will be built in Cadarache, France, by a six-party consortium (European Union, Japan, Russia, U.S, China, and Korea). It is expected to produce 500 megawatts of fusion energy for 400 seconds of operation after it becomes operational in 2020. Contributions from the U.S. include diagnostics, superconducting central solenoid magnets, physics analysis, and tritium handling. Livermore is contributing to the central solenoid and diagnostics. ITER construction will begin in 2006.

"Although tremendous strides have been made over the past decade, scientific questions still remain. For example, we want to understand how the fusion plasma spontaneously forms an insulating surface layer a few centimeters thick where the temperature drops from 40 million degrees to a few thousand," says Livermore fusion scientist Dave Hill.

Hill maintains that the biggest technological challenge for magnetic fusion energy is developing advanced materials that can survive a harsh environment; the economics of fusion energy is also challenging. In the future, fusion engineers must replace steel with materials such as vanadium and ceramics, or find ways to protect the vessel wall material, for example, with a thick liquid layer. He also notes that modeling magnetic fusion processes is particularly difficult because space scales must range from a few millimeters to meters, and time scales from millionths of a second to hours. A new code, TEMPEST, is under development by Livermore scientists to simulate the insulating plasma surface layer.

Using Lasers to Achieve Fusion

Another way to achieve controlled nuclear fusion is to implode BB-size capsules of frozen fusion fuel to the needed temperatures and densities using laser energy. This technique, called inertial confinement fusion, was pioneered at Livermore. Under the high densities involved in this concept, the fusion burn occurs in less than 100 trillionths of a second, and the inertia of the fuel itself provides the necessary confinement.

According to physicist John Lindl, former Livermore Director Johnny Foster appointed Ray Kidder to lead the Laboratory's first small laser fusion program in 1962. Beginning in 1960, John Nuckolls, Stirling Colgate, Ron Zabawski, and other physicists used weapons design codes to calculate the indirect drive approach to igniting fusion microexplosions. It seems possible that giant lasers might someday be focused to compress and ignite a small quantity of deuterium–tritium fuel for weapons applications. The challenge of inertial fusion is that laser heating alone is not enough to generate net energy, even with lasers as large as 1 megajoule. To achieve energy gain, the laser also must compress the fuel to 1,000 or more times its liquid density.

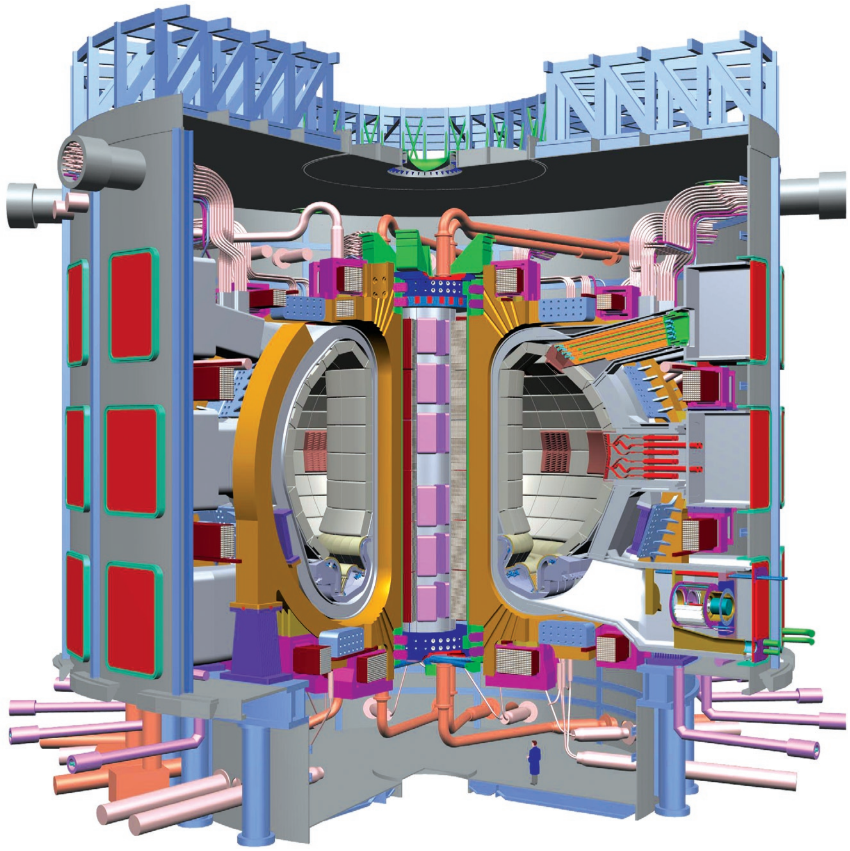
"Compression is the key issue," says Lindl. "If we could compress the fuel to a high enough density while heating a small fraction of it to the temperatures required for fusion, we could achieve ignition and significant gain with a reasonable-size laser." The ignition pellets being designed for the National Ignition Facility (NIF), which is undergoing final assembly in Livermore, will be compressed to a density and temperature about 10 times those that exist in the center of the Sun.

In 1972, Livermore's laser fusion efforts expanded with the formation of the Inertial Confinement Fusion (ICF) Program. Its goal was to demonstrate fusion in the laboratory and to develop laser science and technology for both defense and civilian applications. Experiments were carried out on a succession of increasingly sophisticated lasers—Janus, Cyclops, Argus, Shiva, and Nova. "We continually bootstrapped our capabilities and knowledge," says Lindl.

With Nova, researchers made good progress on laser fusion codes, diagnostics, and target design and fabrication. Livermore's laser fusion research also took advantage of underground experiments conducted at the Nevada Test Site (NTS). The data from Nova and NTS experiments guided scientists in planning NIF.

As part of Livermore's NIF Programs Directorate, the current ICF Program advances design, fabrication, target experiments, and fusion target theory. The Laser Science and Technology Program advances the required laser and optical science and technology both for NIF and for future lasers that might be suitable for fusion energy applications. Much of this research supports DOE's Stockpile Stewardship Program to maintain the U.S. nuclear deterrent. Another goal is exploring ICF as a clean and inexhaustible source for commercial electric-power production.

In 2004, NIF's Early Light experiments met the first milestone of Livermore's ICF Program. Ultraviolet light from NIF's first quad of lasers was aimed at gas-filled targets. The tests showed good agreement between calculations and the observed beam propagated through the target. "These experiments were very successful," says Lindl.



Livermore researchers are helping to design and build the International Thermonuclear Experimental Reactor (ITER). The 10-meter-diameter ITER will produce 500 megawatts of fusion energy for 400 seconds at a time. (Published with permission of ITER.)

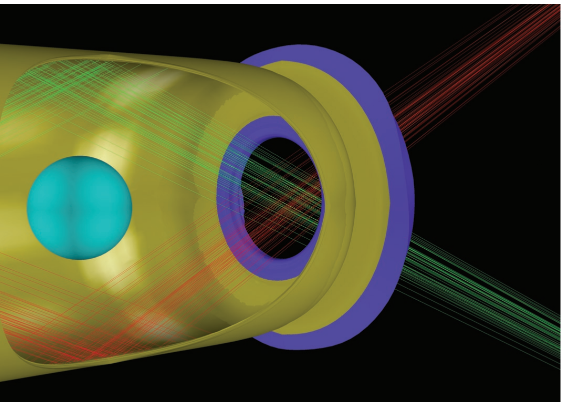
Nuclear Weapons a Popular Icon

Einstein was sometimes—and unfairly—called the "father of the atomic bomb." He did not foresee the release of enormous amounts of destructive energy by bombarding the nuclei of atoms. However, building on the many advances in nuclear physics that occurred after the $E = mc^2$ paper, Otto Hahn and Fritz Strassman discovered nuclear fission in uranium in 1939. Later that year, Leo Szilard conceived a way to use fission in a self-sustaining chain reactor.

Aware of the progress that had been made splitting uranium atoms, Szilard and other scientists feared that Germany might be working on an atomic bomb. In late July 1939, Szilard visited Einstein to finalize the draft of a letter to warn President Franklin D. Roosevelt of the danger. The Laboratory's cofounder, Edward Teller, drove Szilard to Einstein's summer cabin on Long Island and joined them in the meeting.

The Einstein letter to Roosevelt dated August 2, 1939, helped set in motion the Manhattan Project, the mammoth effort to build an atomic bomb. Einstein did not participate in the Manhattan Project, and, in 1946, he became chairman of the Emergency Committee of Atomic Scientists, whose goal was to place nuclear energy under international control.

The bomb that was dropped on Hiroshima had an explosive force equivalent to 15,000 tons of TNT. The Hiroshima bomb was a purely fission device, using the same nuclear process as occurs in nuclear reactors. In contrast, all current U.S. nuclear weapons rely on



The ignition pellets being designed for the National Ignition Facility (NIF) will be compressed to densities and temperatures about 10 times those that exist in the center of the Sun. In this HYDRA simulation of an ignition target for NIF, laser beams are seen entering one end of a capsule called a hohlraum, which contains the fusion fuel (blue). The beams strike the inside of the hohlraum wall and create x rays that cause the capsule to implode and release energy.

a mixture of fission and fusion for their explosive power.

Bruce Goodwin, associate director for Defense and Nuclear Technologies, says most people's immediate reaction to $E = mc^2$ is the recollection of a photo or movie of an atmospheric nuclear detonation. "A nuclear weapon is the icon for $E = mc^2$ because it presents the possibility of Armageddon," he says. "However, the deployment of nuclear weapons among the world superpowers has led to a state of deterrence, which kept the Cold War cold." Indeed, the number of deaths caused by war has dropped precipitously since 1945, when atomic bombs were dropped on Hiroshima and Nagasaki.

Goodwin points out that during the Cold War, the Soviets were rational adversaries. Although they enjoyed significant advantages in conventional armaments, particularly in the early stages of the Cold War, they knew that any attack would be met with NATO nuclear weapons, if necessary. "Nuclear weapons successfully prevented world-scale war while East and West were foes," Goodwin says.

Although the possibility of a crisis that could lead to an Armageddon has been dramatically reduced, the danger of a single nuclear detonation by a terrorist group or rogue nation has increased. In addition to supporting stockpile stewardship, one of Livermore's primary national security missions is to prevent nuclear weapons, materials, and know-how from reaching the wrong hands.

Many scientists, like Goodwin, argue that the world needs to move to a fusion economy. "Nuclear weapon designers have understood fusion for 50 years. The challenge is to harness that understanding for producing civilian energy." He notes that NIF will be the first laboratory to have controlled nuclear fusion, a critical step toward clean and abundant energy. In that light, $E = mc^2$, Goodwin says, offers to transform life on Earth because of the prospect of abundant clean energy.

"Lawrence Livermore, with its expertise of nuclear weapons, the environment, and fusion, is uniquely poised to be a world leader in energy and in keeping the peace."

—Arnie Heller

In the current era of no underground nuclear testing, Livermore researchers participate in the nation's Stockpile Stewardship Program, which uses, in part, advanced simulation technology. Visualization engines turn the data produced by supercomputers into images displayed on individual computer monitors, large-scale screens, or massive powerwalls, such as the one shown above. Simulations help scientists better understand how weapons materials age and how they perform under extreme conditions.

Key Words: Albert Einstein, $E = mc^2$, fission, fusion, Highly Enriched Uranium (HEU) Purchase Agreement, inertial confinement fusion, International Thermonuclear Experimental Reactor (ITER), magnetic fusion energy, Main Injector Neutrino Oscillation Search (MINOS), Main Injector Particle Production (MIPP), National Ignition Facility (NIF), neutrinos, SSTAR (small, sealed, transportable, autonomous reactor), Stockpile Stewardship Program.

For information on Lawrence Livermore's activities for the World Year of Physics, see www.llnl.gov/pao/WYOP.